A wide-field hybrid X-ray telescope for a lunar-based gamma ray burst observatory

Paul Gorenstein*
Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Cambridge, MA 02138-1516 USA

ABSTRACT

Gamma ray bursts have become as important as supernova in astrophysics and cosmology and they should be studied with the same amount of diligence and continuity. Most of the types of telescopes and detectors needed already exist and in fact have already been in space. The addition of a very wide field, high angular resolution X-ray telescope would open a much larger window to bursts whose spectra are soft, either intrinsically or as a result of high redshift. Sensitivity in the X-ray band also benefits from the large number of photons of the X-ray afterglow. To fill that role we describe a telescope that is a lobster-eye optic in one dimension and a coded aperture in the other. It has larger area and bandwidth than a two-dimensional lobster-eye optic but is subject to more background. A permanent site that can accommodate a complete set of instruments that covers the entire energy range from soft X-ray to gamma ray would be preferable to the current practice of launching new spacecraft periodically with instruments that cover only part of the range. Astronomers generally favor free space, over the Moon as an observatory site. However, the architecture of a gamma ray burst observatory is more compatible with a lunar base than is the typical observatory. The instruments can be delivered gradually and perhaps at lower cost to the astrophysics budget through an Earth-Moon transportation system that is supported by the Exploration program.

Keywords: gamma ray bursts, X-rays, Moon, lunar base

1. INTRODUCTION

1.1. Lunar exploration initiative and gamma-ray bursts

Early in 2004 in a speech at NASA Headquarters President Bush presented a "new vision" for space exploration by calling upon NASA to "gain a foothold on the Moon and to prepare for new journeys to the worlds beyond our own" but without offering any significant increase to the NASA budget. The reaction of the astronomical community was rather mute if not negative because implementing the "new vision" means that funding would be diverted from highly regarded future astronomy and astrophysics programs whose preferred sites are HEO or Sun-Earth L2 in space rather than on the Moon. Nevertheless, the lunar exploration program is likely to proceed so it is worthwhile considering whether any future high energy astrophysics observatory can be made compatible with the Moon and perhaps even identify ones where a lunar site is preferable. We present reasons why the Moon is at least as good a site as free space for a permanent gamma ray burst observatory. We also describe a very wide field focusing X-ray telescope that would be an important addition to a set of instruments that detects and provides precise positions of gamma-ray bursts.

1.2. Gamma-ray bursts and their cosmological significance

Gamma ray bursts (GRBs) are the most powerful explosions in the Universe since the Big Bang. They occur at a rate of approximately once per day as brief, but intense, packets of gamma rays and hard X-rays lasting from a few milliseconds to hundreds of seconds. In most cases they are followed by a softer X-ray afterglow of much longer duration. Beginning with the announcement of their existence in 1973 [1] the importance of and interest in GRBs continues to grow as the number and diversity of the events increase. **BATSE** of **CGRO** catalogued several thousand events whose isotropic celestial distribution suggested an extragalactic origin. [2]. That was confirmed by the Italian-Dutch **BeppoSAX** mission, which provided celestial positions that were precise enough to identify the bursts' origin as

* pgorenstein@cfa.harvard.edu; phone 1 617 495-7250

Optics for EUV, X-Ray, and Gamma-Ray Astronomy III, edited by Stephen L. O'Dell, Giovanni Pareschi
Proc. of SPIE Vol. 6688, 668807, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.728645

distant galaxies [3]. Identifications enable optical astronomers to determine the distance and luminosity of a burst, to study the nature of the host galaxy and the internal effects that result from the propagation of shock waves produced by the GRB. **BeppoSAX** also detected the existence of X-ray afterglows that persist for hours and often days following the event. Some GRBs are associated with visible core collapse supernova and others are definitely not although the energy release is about the same. While phenomenological classification schemes have been suggested such as "short duration, hard spectrum" vs. "long duration, softer spectrum", as more events accumulate their behavior is increasingly diverse particularly when their X-ray afterglows are taken into account. There are events where the total energy emitted during the X-ray afterglow phase exceeds that of the prompt GRB emission.

The cosmological significance of GRBs became very prominent when one was found to originate from a host galaxy with a redshift of z = 6.4 [4]. This distance is nearly as large as that of any galaxy or quasar that has ever been detected. The distance to quasars peaks at z = 2 and they are largely gone by z = 5. Considering that the amount of time and the number of facilities that have been devoted to searching for high redshift galaxies in visible light are so much larger than they are for GRB counterparts it would not be surprising if the highest redshift galaxy, i.e. the earliest galaxy, is found as a result of a GRB identification. Very highly redshifted GRBs, i.e. z > 10, if they do exist may make lack a host galaxy because they occurred prior to the era of galaxy formation. The most distant GRBs could possibly be signals from the first generation of stars that were massive and evolved very rapidly to core collapse hypernova to initiate the epoch of reionization.

1.3 X-rays and Gamma-ray Bursts.

Almost all of the thousands of GRBs detected to date were found in the hard X-ray band**.** A smaller number of X-ray selected events were detected by **BeppoSAX** and **HETE 2** [5]**.** There are fewer perhaps because soft X-ray detectors have not had as much sensitivity or sky coverage as hard X-ray detectors.

The spectra of GRBs originating from a larger distance will experience a larger redshift and be spread out over a longer interval of time. Gamma rays will be downshifted to X-rays and the X-ray component will be softer. The mean value of z of the GRBs detected in the 15 to 150 keV band by **Swift** is about 2 and the average photon number spectral index is -1.6[1]. GRB photons from z = 10 with the same energy at their source will appear nearly a factor of 4 lower in energy. Because GRB photon spectra generally decline above 150 keV more photons will be redshifted out of the 15 to 150 keV band than into it. That is, more distant GRBs should be richer in X-rays. Also, X-ray afterglows of GRBs follow seamlessly to increase the signal and compensate in part for the reduction in the number photons due to the larger distance of a z = 10 event compared to z = 2, a factor of ~45. In addition, according to certain models the prompt emission is likely to be beamed in a narrower cone angle than the X-ray afterglow. As a result there would be a class of events where X-ray afterglows but no prompt gamma-ray emission are seen. The conclusion is that the search for very distant GRBs and those without the prompt emission should include a very wide field X-ray/soft X-ray high angular resolution telescope in the complement of instruments devoted to detecting and positioning GRBs. In the following section we describe an X-ray telescope with the requisite capabilities.

2. THE X-RAY TELESCOPE: LOBSTER-EYE PLUS CODED APERTURE

2.1 Telescope Concept

As shown in Fig 1 a hybrid lobster-eye/coded aperture telescope focuses in one dimension by use of a lobster-eye geometry and is a coded aperture imager in the other [6]. The method of focusing is based upon a concept originally described by Schmidt [7]. The reflectors are all identical glass or silicon flats. For the purpose of estimating sensitivity we assume their dimensions are 80 cm x 10 cm x 0.03 cm. They are equally spaced by 6 arc min along 120 degrees of the circumference of a circle. Each flat's 10 cm edge lies along a radius of the circle. The long dimension of the flat is parallel to the axis of the cylinder. X-rays are reflected by either of the two faces depending upon the source direction.

[1] As of August 1, 2007 from table of GRB properties available at http://heasarc.gsfc.nasa.gov/docs/swift/archive/grb_table/

For convenience or to ease fabrication and assembly the 80 cm length can be divided into a linear series of smaller coplanar flats. A cylindrical coded mask consisting of a pseudo random distribution of open and closed circular slits surrounds the circular array of flats. They provide angular resolution in the non-focusing dimension by the same technique used very successfully in two dimensions by instruments aboard **BeppoSAX**, **INTEGRA**L and **Swift**. Small-scale lobster-eye telescopes of this type were constructed and tested [8,9]. The detector is a two-dimensional position sensitive (~ 1 mm resolution) partial cylinder whose radius is half that of the array of flats and is concentric to it.

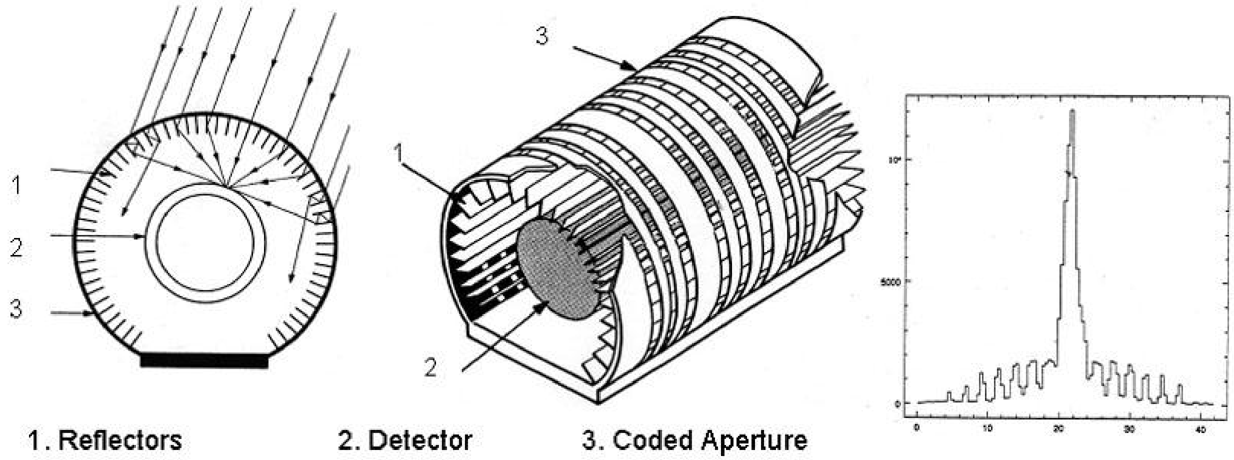

Fig. 1. The lobster-eye/coded aperture hybrid X-ray telescope is shown in the left and center panels. The maximum graze angle is greatly exaggerated. The measured focusing point response of a prototype is shown in the right panel. The side lobes are rays that go straight through the telescope or are reflected an even number of times.

Its area is about a square meter. Currently the only practical soft X-ray detectors with an area of such large size are gas electron multipliers (GEMs), which are essentially evolved position sensitive proportional counters. They are used extensively in experiments at particle accelerators [10]. The cylindrical face of the detector can be approximated by a polygon of flat detectors.

The point response function of a one-dimensional lobster-eye telescope is a central line peak accompanied on both sides by a series of smaller peaks as shown in the right panel of Fig. 1. They are mostly X-rays that reach the focal plane without being reflected. Their positions are fixed with respect to the main image. They add to the signal but increase the amount of diffuse X-ray background admitted. Unreflected diffuse X-rays reduce the sensitivity for detecting GRBs whose photons arrive over a long period of time either as a result of high redshift or because they are from the afterglow phase. On the other hand, when the GRB is easily resolved from background straight through rays from the GRB provide more photons for spectral and temporal measurements.

A 2D lobster-eye telescope forms point images but also an array of fainter point and linear images from X-rays that are singly reflected or go straight through [11]. It has substantially less collecting area and bandwidth than the 1D hybrid. It can be constructed by placing two orthogonal 1D telescopes in series. It would be necessary to change the shape of the reflector in the long dimension from a flat to a segment of circle (or a series of flats arrayed along a circle) to match the envelope of the circular array of flats in the other dimension. The telescope would be two orthogonal partial spheres or more likely an array of linear segments approximating the spherical surfaces. Fraser et al described a more elegant method of constructing a 2D lobster-eye telescope for eventual use in space [12]. They slumped an assembly of square channel plates, which are similar is some respects to the circular channel plates of the **Chandra** HRC and **ROSAT** HRI detectors, along a spherical surface. The limitations of channel plate lobster-eye telescopes are possible difficultly fabricating very large areas or adding a heavy metal coating to the interior walls of the very small channels.

Neither of these two focusing wide field telescopes would replace an essential component of a GRB observatory, which is a more sensitive, higher resolution Wolter telescope like the ones used by **BeppoSAX** and **Swift** to point at the GRB position as soon as possible to refine its position for transmission to Earth, and to study the spectral evolution of the X-ray afterglow [13]. In the future the focal plane detector would be a very high energy resolution cryogenic device that is much more capable of detecting emission and absorption lines than solid state detectors and the telescope would have larger area. However, the pointed telescope can observe only one afterglow at a time and misses their birth. New GRBs occur nearly every day. Albeit with much less sensitivity than the Wolter the lobster-eye telescopes can study the afterglows of many simultaneously from birth to as long as they remain sufficiently intense and within the field of view thereby possibly detecting important very early or late resurgent afterglow features that would otherwise be overlooked.

2.2. Comparing the wide field X-ray telescopes

Table 1 compares the theoretical 0.5 to 5 keV performance of three species of wide field X-ray telescopes with the same dimensions: a two dimensional coded aperture, a two dimensional lobster-eye telescope, and the lobster-eye/coded aperture hybrid. All have the same 80 cm focal length, the same detector dimensions, and the same total sky coverage of 3.1 ster (0 to 60 degrees from the local vertical). The angular pixel size is 6 arc min x 6 arc min. The extraneous line images doubles the diffuse background in the hybrid telescope. Singly reflected rays and rays that are not reflected by the 2D lobster eye telescope increase diffuse background considerably more but detection of GRBs is more likely to be photon limited than background limited. The discrete cosmic X-rays sources are resolved for the most part by the focusing telescopes and their influence is confined to the region of their images. However, the presence of discrete cosmic sources in the field of view of the coded aperture detector triples the background on the average, more when the galactic plane is in the field of view and less at other times. The soft X-ray sensitivity of both types of lobster-eye telescope is superior to that of the coded aperture and they likely to provide positions that are more precise. Nevertheless, a coded aperture telescope like **BAT** of **Swift** would still be an essential component of the GRB observatory by covering the hard X-ray band where most GRBs are detected currently.

Table 1
Comparison of 3 Types of Wide Field (3.1 ster coverage) X-Ray Telescopes

	Coded Aperture	**1-D Lobster-eye + 1-D Coded Aperture**	**2-D Lobster-eye**
Angular acceptance of diffuse background in source region	3.1 ster (half sky)	3.7×10^{-3} ster	3.0×10^{-6} ster
0.5 keV Effective Area	3200 cm^2	200 cm^2	14 cm^2
1 keV Effective Area	3200 "	141 "	13 "
5 keV Effective Area	3200 "	58 "	3 "
$(0.5 - 5\text{ keV Background})^{0.5}$ for 5 seconds	1800	14	(negligible)
Relative Sensitivity	1.8	4	photon limited

It is not obvious which of the two lobster-eye devices is superior for detecting high redshift GRBs, which have presumably softer spectra and are much fainter than the events detected currently. The 1-D telescope with at least ten times more collecting area is preferable where detection by the 2D telescope would be photon limited. On the other hand if the GRBs and their afterglows persist at a low rate over a long enough period of time the detection sensitivity of the 2D telescope will eventually overtake the 1D's. However, if the GRB is well above background the much larger number of photons collected by the 1D device makes it superior for spectral and temporal measurements.

3. THE MOON AS AN OBSERVING PLATFORM

3.1 Perspectives of the astronomical community

The question whether or not the Moon is a desirable site for an astronomical observatory evokes mostly but not universally negative reactions from astronomers. The differing views of R. Giacconi and R. Angel are reported in a 2004 issue of *Science* [14] and those of P. Lowman and D. Lester in the Nov. 2006 edition of *Physics Today* [15]. Giacconi expresses the negative position of the majority, by noting that the issue involves not only comparing the Moon's accommodations to free space's but whether space science, astrophysics especially, which has had spectacular success operating robotically in free space during the past 36 years should become entangled in the problems of human exploration of the solar system, which has been stagnant during the same period and faces substantial problems in restarting. In particular proponents of the next generation observatory missions most definitely prefer free space and certain programs notably the Laser Interferometer Space Antenna and the Terrestrial Planet Finder are incompatible with a lunar site.

Advocates for a lunar-based observatory should be able to show that the Moon offers an actual benefit. They are radio astronomers that believe the stability of the Moon makes it an exceptional site for high-resolution radio interferometry. Others point out that the backside of the Moon is completely shielded from the Earth's radio transmissions making it the quietest site in the solar system. Advocates for a lunar-based optical liquid mirror telescope (LMT) would utilize the Moon's low but finite gravity force and absence of an atmosphere to create an extremely large diameter telescope whose capabilities could not be matched by either a ground based or orbiting telescope. A pan containing a reflective liquid is rotated about a vertical axis to create a near perfect parabola. With the future development of suitable mechanical bearings that work smoothly in vacuum the diameter could be as large as 100 m, which is far larger than any that has been proposed for space. The angular resolution and sensitivity would be excellent. When placed within a crater located near a lunar pole, the temperature would be stable and low enough to support IR studies without additional cooling. Although the pointing direction of the LMT is restricted to the zenith, and near a pole the LMT would view only a small field of the sky, with the very slow rotation of the Moon its proponents claim it would observe objects 5 magnitudes fainter than is possible with the future **JWST**. The University of British Columbia and Laval University are developing a ground based LMT and in collaboration with the Stewart Observatory are studying a prospective lunar-based LMT [16].

3.2 Advantages of a lunar base for a permanent GRB observatory

3.2.1 Instruments, delivery, and accommodations

Two aspects of a GRB observatory, its architecture and its permanency, make the Moon a favorable site. The traditional observatory architecture consists of a large telescope as the centerpiece plus a number of focal plane detectors that are subsidiary to it. The telescope observes by pointing to specific targets. In contrast the GRB observatory would consist of a distributed set of wide field instruments like those listed in Table 2, which are approximately of equal size. They all point at the zenith and operate independently. The appropriate accommodation for them is a stable platform with abundant space. The instruments can be deployed gradually; they need not all be present at the beginning and they can be replaced when failed or obsolete. This calls for a site with a large area that is revisited on occasion.

The creation of a lunar-based GRB observatory is contingent upon the existence of a lunar base with an infrastructure plus an Earth-Moon transportation system that can take the instruments as cargo. There should be astronaut or robotic services to deploy them. The instruments can be delivered incrementally over a period of time as the GRB observatory can function usefully without the full complement of instruments being present. When completed the components of a permanent GRB observatory should include all of the items listed in Table 2.

Table 2
Components of a Permanent GRB Observatory

Instrument	Energy Band	Positioning Accuracy
"All-sky" Gamma-ray detectors	0.1-30 MeV	Few degrees
Wide field (3 ster) coded aperture hard X-ray detector	10-200 keV	Few arcminutes
Wide field (3 ster) lobster-eye telescope, 1D hybrid or 2D	0.5-10 keV	~ 0.5 arcminutes
Robotic Wolter telescope on 2-axis pointing system with high energy resolution cryogenic detector in focal plane	0.2-10 keV	~ 1 arcsecond
UV/Aspect telescope co-aligned with Wolter telescope	UV and aspect	~ 1 arcsecond

In addition there would be the usual support systems, namely Sun, Earth, and zenith star sensors plus computer, power system, and communication system in continuous contact with the Gamma-ray Burst Coordination Network (GCN).

With the exception of the lobster-eye telescope all of these instruments types have already operated in space. However, the soft X-ray lobster-eye telescope is likely to be the instrument that best detects and locates bursts with very high redshift. All of the instruments present would view a large region of the sky overhead simultaneously. A burst position with arc minute precision found by either the lobster-eye telescope or the coded aperture would be transmitted to the GCN. Following the procedure of **Swift** the Wolter telescope and UV/aspect telescope would rapidly point to the burst position to study the X-ray afterglow. The action of the Wolter X-ray telescope would be similar to that of the ground based optical and IR robotic telescopes like PARITEL, RAPTOR, and ESO's REM that respond rapidly to point at new GRB and supernova positions. The Wolter telescope will refine the position to arc second accuracy and promptly relay it to the GCN so that ground based or space based optical/IR and radio telescopes who have not already found their target can do so and study the event's afterglow, identify the host galaxy, determine the location of the GRB within it and observe the internal reverberation effects resulting from propagation of the GRB shock waves.

The lunar-based GRB observatory is not subject to the limitations of a single launch. Its components can be delivered to the Moon, over the course of several missions. The size of the observatory would not be constrained by having to fit within a spacecraft envelope of limited size. Nor is the mass of the observatory limited to the lift capacity of a single launcher. The instruments are essentially independent and can be set down on the Moon without constraints other than that they point at the zenith with an unobstructed view of a region with a radius of about 60 degrees.

The alternatives to a lunar based GRB observatory with the same complete set of instruments are (1) the development and launch of a fully integrated, inflexible payload that may be even more massive than CGRO, or (2) dividing the instruments among several smaller spacecraft that are launched separately and operate independently. In the latter case many GRBs would not have complete energy coverage and data processing and archiving would be complex operations. Neither alternative allows servicing or replacement of failed or obsolete instruments. Therefore, neither can be a permanent GRB observatory.

3.2.2 Stability of the lunar platform and the Moon's rotation

Without an atmosphere or significant seismic activity the Moon is a very stable platform. After they have been deployed and have settled into place the alignment of the telescopes with the local vertical and azimuth will be constant, although there should be an allowance for possible temperature dependence. Numerous X-rays sources whose celestial positions are known will be traversing the field of view of the telescopes frequently. They will make it possible to measure the orientation of the instrument on the celestial sphere very accurately at all times. Because the Moon's rate of rotation is known, as the sources traverse the field of view we can calibrate with great accuracy the transformation of detector coordinates to celestial coordinates for all conditions. With minimal aspect uncertainties and excellent knowledge of the relation between detector and celestial coordinates the error in the position of a GRB will be no larger than the statistical error of determining the centroid of an image whose size is several arcminutes.

X-ray afterglows and possible precursors

As the Moon rotates the X-ray afterglow of a GRB will remain in the field of view of the lobster-eye telescope and be under continuous observation for two weeks on average. An unlimited number of the declining but occasionally resurging afterglows of older GRBs can be studied as long as they are still detectable. The narrow field Wolter telescope will usually be observing the afterglows of only the most recent GRBs where its high energy resolution detector would be most effective. Also, as the Moon rotates the afterglows of GRBs whose prompt emission was detected earlier by the wider field gamma ray detectors will enter the field of view of the X-ray telescope. In many cases their positions would be determined and forwarded to the GCN network. It will be possible to search for soft X-ray precursors to GRBs.

Other transients and X-ray surveys

In addition to GRBs and their X-ray afterglows the data archives of the wide field soft X-ray lobster-eye telescope will contain other important information. It will detect transient galactic sources and continually survey a broad expanse of the sky to significantly greater depth than before.

3.3 Lunar Base Issues

3.3.1 Site selection and the thermal Environment

A site that is selected for human habitation is likely to be compatible with a GRB observatory. Equatorial sites are the least desirable and probably untenable for both humans and observatories because of the temperature extremes from lunar day to night. At the equator the temperature of the surface varies between 390 K at the peak of lunar day and 100 K at the low point of the lunar night. The temperature range and the absence of solar power during lunar night are factors that make equatorial sites extremely inhospitable for both humans and telescopes. Also, near the equator the Sun will transit the field of view, a condition that would be especially problematic for the soft X-ray telescope. At higher latitude the maximum temperature is lower and the day/night variation is more moderate. Above 60 degrees the Sun would not be in the direct field of view of the X-ray telescopes. Consequently the GRB observatory site should be at high latitude.

Water is essential for human presence and there is evidence from the Clementine mission that ice exists at the lunar poles, the south pole particularly. In permanently shadowed regions, e.g. the floor of a crater near a pole, the temperature is a constant 40 K. This is cold enough to permanently trap water molecules that have been introduced by comets or water-bearing meteoroids. Ice would probably not have to be transported a great distance from the regions permanently in shadow to human habitats near a pole. Illumination maps have be made of the Moon's polar regions from Clementine's images [17, 18]. There exist regions near the north pole that are illuminated full time to varying degrees and the temperature range is 223 +/- 10 K, a comparatively benign thermal environment for both humans and a GRB observatory. Electric power can be provided to regions that are illuminated insufficiently from a solar array situated at a higher point, e.g. a tower above a crater high enough to clear the topography to have a continuous view of the Sun.

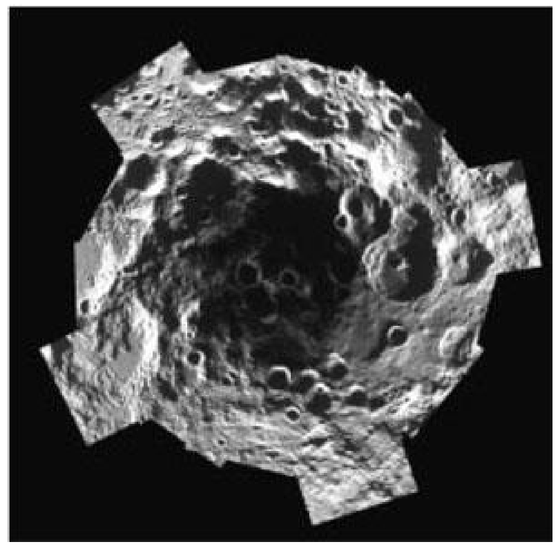

Fig.2. Mosaic of Clementine images of the Moon's south pole showing dark and illuminated areas, Bussey, et al.[17]

NASA is considering the Shackleton crater near the south pole as the site of the lunar base.

3.3.2 Lunar dust and micrometeorites

Lunar dust is pervasive, adheres to any material, and is a nuisance in general. A considerable quantity will be stirred up when an instrument is deployed. The dust avoidance strategy would be to keep mechanical covers of all instruments closed until deployment is complete and "the dust has settled". Electrostatic shields will be employed as well other dust mitigation techniques that will be developed for lunar activities. Micrometeorites are the agent responsible for the creation and dispersion of lunar dust. However, it is known that buildup rate of lunar dust is extremely small as shown by the continuing operations of the laser reflector that was planted on the Moon over 35 years ago for precise tracking of the Moon's distance from the Earth.

Direct strikes by micrometeorites have so far not caused any X-ray telescopes or detectors in orbit to fail and there is no reason to believe the rate of direct strikes will be higher on the Moon. (With no alternate explanation there is a possibility that a bad pixel in an XMM-Newton CCD was caused by a micrometeorite.). The ejecta from a micrometeorite that strikes the lunar surface would be widely dispersed and the impact of the fraction that falls upon the instruments would be much less severe. Moreover, if an instrument of a lunar-based GRB observatory does fail as a result of a micrometeorite strike or for any other reason it can be replaced.

3.3.3 Service requirements

The GRB observatory requires power for operation and thermal control as well as communications services. Presumably, the lunar base will provide electric power from a central station fed by a large array of solar collectors. The Moon's equatorial plane is only 1.53 degrees off the ecliptic so the Sun's angle with respect to the zenith at any point on the Moon is essentially the same as the latitude. As discussed above at a high site near either of the two poles solar power will be available full time.

In order to transmit GRB positions it is necessary to be in continuous communications contact with the Earth. Sending the position coordinates of a fresh GRB requires only a very small amount of data to be transmitted so it should be possible to give its transmission very high priority whenever an event has been detected and its positioned determined. Other data can be sent more slowly at opportune times. Due to the Moon's librations, which are an apparent 6.5 degree nodding of the poles due to the different inclinations of the Earth's and Moon's rotation axes, there are periods when the poles do not have a direct view of the Earth. To maintain constant communications contact between a lunar base near a pole and Earth there is a proposal to place three relay satellites in a high eccentricity orbit over the pole

4. SUMMARY AND CONCLUSIONS

The study of GRBs, their afterglows, and their host galaxies has been extremely productive. The need to detect and optically identify them will persist regardless of how many GRBs are found by **Swift** and other spacecraft. As GRBs are found at larger distance the studies assume more cosmological significance. The most distant GRBs are likely to be fainter, be spread out over a longer time interval and have softer spectra. These features and the existence of a strong diffuse X-ray background as well as intense galactic sources make a focusing telescope the appropriate device to detect GRBs in the X-ray band. The wide field soft X-ray telescope could be either a 2D lobster-eye with lower background or a hybrid 1D lobster-eye/coded aperture with larger area. With further study one or the other may prove to be more effective.

GRBs are important enough to merit a permanent dedicated observatory that covers the entire energy range from soft X-rays to gamma rays. The architecture of a GRB observatory differs from a conventional observatory where a large telescope points in different directions at specific targets. In contrast, the GRB observatory consists of a set of independent very wide field telescopes and detectors of more or less equal size that are aligned with the zenith. They would benefit from being on a very stable platform. If the lunar exploration program does proceed to the establishment of a lunar base, the capacious, very stable lunar surface would be the appropriate site to host the GRB observatory. The instruments could be delivered incrementally according to the availability of cargo space. Obsolete or failed instruments can be replaced. A high latitude site is preferred if not essential because solar power is available for a larger fraction of the time and day/night temperature variations are more moderate than at the lunar equator. Also the Sun can be kept outside the field of view of the X-ray telescopes. The GRB observatory is compatible with the near polar site that is likely to be selected for the lunar base..

REFERENCES

1. Klebesadel R.W., Strong I.B., and Olson R.A. 1973, "Observations of Gamma-Ray Bursts of Cosmic Origin", *Ap.J.* 182, L85 (1973)

2. Briggs, Michael S.; Paciesas, William S.; Pendleton, Geoffrey N.; Meegan, Charles A.; Fishman, Gerald J.; Horack, John M.; Brock, Martin N.; Kouveliotou, Chryssa; Hartmann, Dieter H.; Hakkila, Jon, "BATSE observations of the large-scale isotropy of gamma-ray bursts" *Ap. J.* 459, 40 (1996)

3. Sahu, K. C. et al (40+ other authors), “Discovery of the optical counterpart and early optical observations of GRB 990712”, *Ap. J.* 540, 74 (2000)

4. Haislip, J.B. et al. (60+ other authors), “A photometric redshift of z = 6.39 +/- 0.12 for GRB 050904”, *Nature* 440, 181 (2006)

5. Sakamoto, T, et al (35+ other authors). “Global Characteristics of X-Ray Flashes and X-Ray-Rich Gamma-Ray Bursts Observed by HETE-2”, *Ap. J.* 29, 311 (2005)

6. Gorenstein, P. and Mauche, C. W., “All-sky high resolution cameras for hard and soft X-rays” *AIP Conference Proceedings No. 115*, *High Energy Transients in Astrophysics*, S. Woosley Ed. (1984)

7. Schmidt, W. K. H., “A proposed X-ray focusing device with wide field of view for use in X-ray astronomy”, *Nuclear Instruments and Methods* 127, 285 (1975)

8. Gorenstein, P., Whitbeck, E., Austin, G.A, Kenter, A., Pina, L., Inneman, A., and Hudec, R., “A lobster eye X-ray telescope prototype”, *SPIE* 2805, 74 (1996)

9. Hudec, Rene; Inneman, Adolf V.; Pina, Ladislav; Hudcova, V.; Sveda, L.; Ticha, Hana, “Lobster-eye x-ray telescopes: recent progress”, *SPIE* 4851, 578 (2003)

10. Barbeau, P.S., Collar, J.I., Geissinger, J.D., Miyamoto, J., Shipsey, I. and Yang, R. “A first production of gas electron multipliers”, *Nuclear Instruments and Methods A*, 515, 439 (2003)

11. Angel, J. R. P. “Lobster eyes as X-ray telescopes”, *Ap. J*. 233, 364 (1979)

12. Fraser, G. W. et al (29 other authors), “Lobster-ISS: An Imaging X-ray all-sky monitor for the International Space Station”, *SPIE* 4497, 115 (2002)

13. Willingale, R.; O'Brien, P. T.; Osborne, J. P.; Godet, O.; Page, K. L.; Goad, M. R.; Burrows, D. N.; Zhang, B.; Rol, E.; Gehrels, N.; Chincarini, G., “Testing the Standard Fireball Model of Gamma-Ray Bursts Using Late X-Ray Afterglows Measured by Swift” *Ap. J.* 662, 1093 (2007)

14. Lawler, Andrew, “Astronomers ponder a really long-range vision for NASA” *Science* 303, 613 (2004)

15. Paul D. Lowman Jr. and Daniel F. Lester, “Build astronomical observatories on the Moon?”, *Physics Today*, November, 59, 50 (2006)

16. Borra, Ermanno F.; Seddiki, Omar; Angel, Roger; Eisenstein, Daniel; Hickson, Paul; Seddon, Kenneth R.; Worden, and Simon P., “Deposition of metal films on an ionic liquid as a basis for a lunar telescope”, *Nature* 447,. 979 (2007)

17. D. Ben J. Bussey, Paul D. Spudis, and Mark S. Robinson, “Illumination conditions at the lunar south pole” *Geophysical Research Letters*, 26, 1187 (1999)

18. D. Ben J. Bussey, Kirsten E. Fristad, Paul M. Schenkt, Mark S. Robinson and Paul D. Spudis, “Constant illumination at the lunar north pole”, *Nature* 434, 842 (2005)